Changes in streamflow and water quality in the upper Oldman River watershed due to climate change and open-pit coal mining development

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1 Introduction

Southern Alberta water resources are known to be under strain due to human and natural factors (Alberta Environment, 2006). The Oldman River basin (ORB) in semi-arid southern Alberta is affected by extensive land use, major irrigation supply dams, large-scale diversions, and allocation/reallocation of water supplies (Byrne et al., 2006). Population and economic growth have put an increased demand on water supply and on water quality. Climate change scenarios suggest increased air temperatures and decreased snow accumulation in the region (Zhang et al. 2019). A modest decline in streamflow has already been observed over the past century for the unregulated rivers upstream of diversion points in the ORB and reflect the effects of climate change (Rood et al., 2005). Enhanced evaporation and transpiration will also likely alter the hydrologic regime, and teleconnections between ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation, Pacific Decadal Oscillation) may enhance or attenuate climate-forcing on the hydrologic regime (Isalm and Gan, 2016).

The ORB has also been affected by increasing physical, chemical, and biological contaminants, and water managers must be prepared for extended periods of reduced-flow conditions that could result in accumulation of water-borne

contaminants (Byrne et al., 2006). In the coming decades, further increases in air temperatures and changes in precipitation patterns are likely to affect streamflow in the ORB and have the potential to substantially alter streamflow patterns and timing. In turn, these changes could have cascading effects on environmental and socioeconomic values; limiting water use for some users and degrading aquatic habitat in the watershed. In addition, the watershed is facing further stress from increased industrial interest in its headwaters. Several proponents have expressed interest, and are in various stages of environmental review, to develop open-pit coal mining operations in the coal-rich portions of the upper Oldman River. In addition to increased water use, open-pit coal mining operations bring renewed concern related to water quality, most notably through concerns of increased selenium concentrations in waterways, which results from oxidation of pyrite in mine-waste deposits. Because selenium bioaccumulates, it can present risk to aquatic ecosystems, including affecting fish (Miller et al., 2013), and in higher levels, risk to human health, and limiting the water's suitability for irrigation or consumption (Lemly, 2019).

The goal of this project is to provide a broad perspective on the variability of water resources in the ORB and outline the potential increase in risks to sustainable water management in the coming decades. The first objective is to simulate two historical 'worst-case' drought scenarios of water supply (i.e., Oldman River near Lethbridge) developed from the instrumental record and a tree-ring reconstructed proxy record and compare historical water supply to current water demand. Second, a hydrological model of the upper ORB was developed in order to simulate streamflow for tributaries and the mainstream Oldman River under a historical period (1989-2019) and to estimate streamflow under two future climate change scenarios (RCP 4.5 and RCP 8.5). Third, we applied the model in an integrated manner to evaluate water use and selenium loading associated with two future mine development scenarios to estimate changes to water quantity and quality in the watershed. The change in water quantity due to water use and climate change is summarized using three hydroclimatic indicators to highlight periods of the year when water quantity is of heightened importance. Concentrations of selenium at all sub-basin outlets were simulated within the hydrological model and compared to water quality guidelines. These results provide a quantitative estimate of potential environmental risks due to climate change and proposed open-pit coal mining in the ORB.

2 Study Area

The Oldman River Basin (ORB) is located in southwestern Alberta (Figure 2.1). The headwaters lie within the Rocky Mountain Natural Region of Alberta, and includes the Alpine, Subalpine, and Montane Natural Subregions, while the lowest reaches near the Oldman Reservoir are part of the Grassland Natural Region. The Rocky Mountain Natural Region is known for cool summers and high annual precipitation, particularly in the winter, and its vegetation consists primarily of coniferous forests, alpine meadows, and exposed rock at highest elevations (Natural Regions Committee, 2006). Grasslands make up approximately 80% of the land area of the ORB (Poirier and De Loe, 2011). The climate is semi-arid with a relatively long growing season and receives the highest level of annual precipitation in June. The eastern portion of the ORB is extensively used for agriculture. Agricultural activities have been enhanced by irrigation since the early 1900s. The expansion of irrigation in the 20th century was accompanied by a sequence of on-stream and off-stream dams and reservoirs and an extensive canal network. The St. Mary River Projects and Lethbridge Northern Irrigation District use both the Oldman River and southern tributaries of the Oldman River and play a key role in economic development as irrigation supports agriculture (Sauchyn et al., 2016).

Natural disturbances including wildfire and mountain pine beetle attack have affected the forests that cover the western portion of the basin, while forest harvesting activities continue presently. Urban development has expanded, primarily along the Crowsnest River in the Crowsnest Pass, including the towns of Coleman, Blairmore, Frank, Bellevue, and Lundbreck. The region has a history of coal mine development dating back to the late 1800s and currently there is renewed interest in developing new metallurgical open-pit coal mines in the Oldman River headwaters and Crowsnest Pass.

Our study area comprises the ORB to Lethbridge at one scale and the 3,150 km^2 area upstream of the Oldman Reservoir as another scale (Figure 2.1). This drainage area includes the Upper Oldman River and the Crowsnest River, a major tributary of the Oldman River that drains the Crowsnest Pass area but does not include the Castle River. The study area is delineated by Hydrological Unit Classification 10 (HUC 10) watersheds as well as Water Survey of Canada hydrometric gauge outlets and major points of interest. The remainder of the Oldman River basin is considered in

aggregate, with outputs for the entirety of the ORB estimated for the Oldman River at Lethbridge hydrometric gauging site.

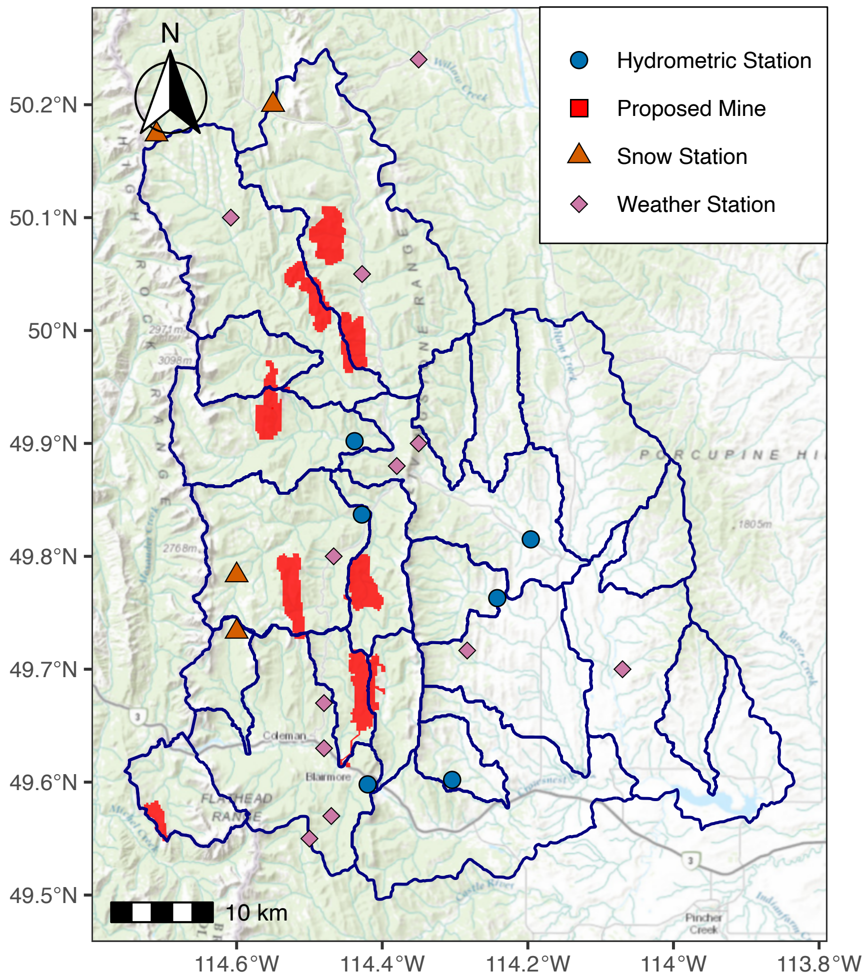

Figure 2.1: Interactive map of the Oldman River study area. Hover over the element to see site name.

3 Methods

3.1 Historical Drought Scenarios

Water supply for the baseline mean (1961-1990) and two historical drought scenarios was determined from naturalized weekly streamflow data for the Oldman River near

Lethbridge (Water Survey of Canada; 05AD007) for the period from 1912-2009. The naturalized flow data were derived from the streamflow record, reservoir data, recorded and estimated irrigation withdrawals, and climate data (CITE).

A tree-ring reconstruction of streamflow was used to derive drought scenarios. Severe drought scenarios were previously derived from a tree-ring reconstruction of the annual flow of the South Saskatchewan River (SSR) from work at the Tree-Ring Lab at the University of Regina (Axelson et al., 2009). Annual growth increments of long-lived and moisture-sensitive trees were measured to within 0.001 mm from high-resolution images of polished wood samples using the image analysis system for tree rings (Sauchyn et al., 2015). Two sustained drought scenarios were presented as the percent departure values from the 1961-1990 baseline mean (Sauchyn et al., 2015). The percent departure values for the two sustained drought scenarios in the SSR basin, of which ORB is a sub-basin, were scaled to the ORB to determine the percent departure from the baseline mean for the tree-ring reconstructed (i.e., proxy) drought. The two drought scenarios include: 1) historical drought, the drought of record in the Canadian Prairies known as the 'dirty thirties', which had low water supply from 1935-1941 and ended with a water surplus in 1942; and 2) proxy drought, a comparable period of eight years in the tree-ring reconstruction from 1717-1724 (Table 3.1). The proxy drought is comparable in terms of duration that ends in a water surplus year (1724); however, the first five years of the proxy drought were much more severe than the analogous 1930s period (Sauchyn et al., 2015). Inter-annual hydroclimatic variability, which includes teleconnections between ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation, Pacific Decadal Oscillation) and the hydrologic regime of the ORB were not considered.

The two sustained drought scenarios were used to compare annual water supply (i.e., naturalized Oldman River streamflow at Lethbridge) with current surface water license use, defined as surface water allocation minus return flow (AMEC, 2009). Surface water license use was compiled in an earlier study of surface water and groundwater license allocations in the ORB (AMEC, 2007). Given that the Alberta Government closed the basin to further surface water allocations in 2006 (Alberta Environment, 2006), we assumed that surface water license use would not have changed. Within the ORB, surface water made up 97.3% (2,231,326 dam^3) of licensed allocation (2.6% groundwater; AMEC, 2007). Surface water licensed use was 92.1% (2,055,620 dam^3) of surface water allocation and 61.5% of median natural annual streamflow (3,343,000 dam^3; AMEC, 2007).

Table 3.1: The sustained drought record from 1935 to 1941 and a similar, but more severe, sustained drought from the tree-ring record scaled to the ORB (Sauchyn et al., 2015); both droughts ended with a comparable year with above average water levels. Percent departure is from the 1961 to 1990 baseline of mean annual naturalized streamflow for Oldman River at Lethbridge.

Sustained Historical Drought		**Sustained Proxy Drought**	
Year	**% Departure**	**Year**	**% Departure**
1935	-22	1717	-47
1936	-40	1718	-62
1937	-21	1719	-29
1938	2	1720	-41
1939	-34	1721	-53
1940	-35	1722	-7
1941	-42	1723	-38
1942	44	1724	41

3.2 Streamflow Simulations

A hydrological model was developed for the upper Oldman River study area under a baseline period (1989-2019) and to estimate streamflow under two future climate change scenarios (RCP 4.5 and RCP 8.5; 2021-2080). The model simulates daily streamflow for 22 sub-basins in the study area, which are located at major tributary outlets, Water Survey of Canada hydrometric gauging stations, and other points of interest. Further details on model formulation, data inputs, and model calibration and verification can be found in Appendix A: Technical Details.

The model domain only simulates streamflow upstream of the Oldman Reservoir, and does not simulate the Castle River, a major tributary of the Oldman River. This simplified model domain reduces model complexity by accounting for a smaller geographic area and avoiding downstream water management infrastructure. A first order estimate of streamflow for the Oldman River at Lethbridge was obtained by calculating weekly fractional differences between streamflow simulations for the model outlet and the Oldman River near Lethbridge (Water Survey of Canada;

05AD007). These fractional differences were averaged by week of year over the 1989-2019 period (ranging from 1.6 to 6.3) and were used to scale model outputs for the Lower Oldman River Above Reservoir sub-basin. These scaling factors are assumed to remain constant into the future; therefore, under future climate scenarios we assume any change in seasonality within the model domain is consistent further downstream in this empirical estimate.

3.3 Hydrologic Regime and Watershed Indicators

Changes in streamflow, the measure of the volume of water carried by rivers and streams, can directly influence ecosystems and human water needs. In the ORB, streamflow varies naturally throughout the year. During the winter months streamflow is generally low since most precipitation falls as snow and accumulates. As air temperatures increase in the spring, melting snow and spring rains increase streamflow, which typically peaks in May or June. The amount of streamflow during this period is important because it accounts for much of the year's water supply. Once the winter snowpack melts, streamflow decreases, typically leading to low streamflow during late summer, fall, and winter. Streamflow during August and September is particularly important because many downstream water users, notably irrigators, depend on water availability during the summer months for crop growth. In addition, low streamflow during the late summer can negatively impact aquatic ecosystems, including poor water quality and limited fish habitat.

Several hydroclimatic indicators were derived from simulations from the hydrological model to capture the effect of a changing landscape and climate on water resources in the upper Oldman River watershed. These are then used to identify changes in streamflow between climate scenarios during key periods of the year and are summarized in Table 3.2.

Table 3.2: Hydroclimatic indicators used to identify changes in hydrologic regime and function.

Variable	**Description**
Annual Flow	The average annual streamflow, representative of the amount of water passing through this point in a calendar year.
Peak Flow	The average April-June streamflow, representative of conditions during snowmelt, which has historically coincided with peak runoff and heightened flood risk.
Summer Low Flow	The average August-September streamflow, representative of conditions following snowmelt, which has historically coincided with summer low flows and heightened risk of droughts, degraded water quality, and water scarcity.

Changes in climate can impact the magnitude and timing of streamflow. For instance, further increasing air temperatures due to climate change are likely to lead to a faster spring snowmelt while additionally leading to higher rates of evaporation during the summer months (Luckman, 1998; Byrne et al., 2006). Likewise, changing precipitation patterns are likely to lead to greater winter precipitation, but also more arid late-summer conditions.

3.4 Mine Development

The hydrological model was run under two future development scenarios to estimate the effect of coal mine development in the study area. The Moderate Scenario assumes the development of only Grassy Mountain and Tent Mountain mines, both located in the Crowsnest River watershed. The High Scenario assumes eight proposed mines are developed: Grassy Mountain and Tent Mountain (Crowsnest River sub-basin); and, Isolation South, Elan South, Chinook Vicary, Cabin Ridge, Isola, and 4-Stack (upper Oldman River watershed). This study integrates the effects of selenium loading on waterbodies and the increased consumptive water use due to mine development into the hydrological model but does not consider the effects of land cover changes nor water management or other mine infrastructure (such as settling ponds, water storage ponds, or in-stream diversions). Further details about the assumptions of each mine scenario and calculations to estimate mine development timeframes, waste rock generation, selenium loads, and spatial locations are provided in Appendix B: Mine Development Assumptions.

3.4.1 Water Use Estimates

Water use was incorporated into the hydrological model for all mines developed in each scenario. Water use for each mine was estimated using reported water use values from Grassy Mountain, which consisted of 900,000 m^3/year in "Plant Make-up Water" and 60,000 m^3/year in dust suppression (Riversdale Resources Ltd., 2016). Of this volume, Grassy Mountain estimates approximately a third of this water is consumptive and therefore is treated as a loss from the system and not returned. This consumptive water use was scaled by the maximum coal production estimated for Grassy Mountain. This value (0.204 m^3/CMT consumptive and non-consumptive, 0.067 m^3/CMT consumptive) was used to correct water use for each year for all mines based on their estimated coal production by year from 2021-2069 (Figure 3.1). Water use for each mine is assumed to be removed from their immediate sub-basin (i.e. no water is piped in or diverted from another water source). Water use is assumed to be constant throughout the year.

We note that since the ORB is closed to new water licenses, the volume of allocated water potentially would not change; however, it is possible that the consumptive use of water could increase or decrease and the point of withdrawal could also be located in a headwater tributary rather than on a larger river. In addition, there is uncertainty in the location and amount of available water that could be obtained by mining proponents, either through purchase of an existing water license or accessing an existing industrial allocation held by Alberta Environment and Parks from the Oldman Reservoir. To reflect this uncertainty, we refer to "potential allocation" throughout this document as the amount of water potentially requested by each mine proponent for industrial operations, including consumptive water use and return flow.

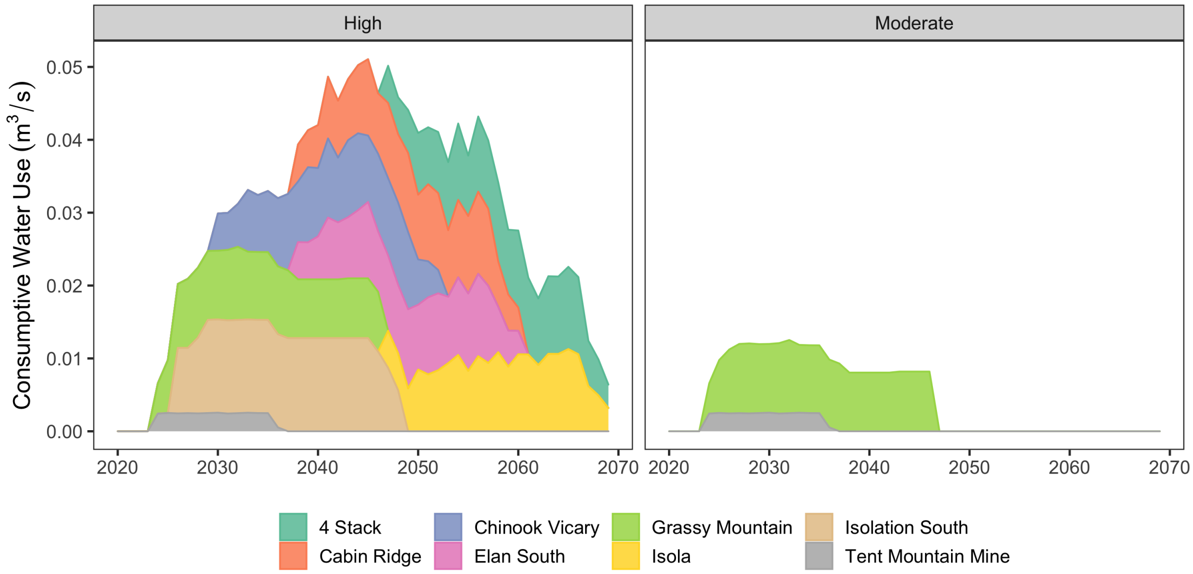

Figure 3.1: Consumptive water use (m^3/s) at each mine under both the Moderate and High scenarios.

3.4.2 Selenium Loading

Mass loading of selenium was estimated for each year, corresponding with the timing of mine development (Figure 3.2). These loading estimates were obtained by scaling the size and coal production of a specific mine against published values in the Grassy Mountain Environmental Assessment (Riversdale Resources Ltd., 2016). Mass loadings were injected into the immediate sub-basin and were assumed seasonally constant and to remain indefinitely following mine closure. In order to account for the sensitivity of selenium attenuation estimates (through mechanisms such as subaqueous waste disposal or contact-water capture and treatment), mass loadings were run under a variety of attenuation rates, from 0% (i.e. no attenuation), 80% (Lower case capture efficiency in SRK Consulting (2016)) to 99% (i.e. almost all selenium is removed at source and not injected to the watershed). Using the hydrologic models built-in contaminant transport algorithm, the mass loading estimates were used to calculate selenium concentrations at source and were tracked at all sub-basin outlets. Background concentrations of selenium were not considered (treated as nil within the hydrological model) as they are substantially lower than the modelled loading from mine development.

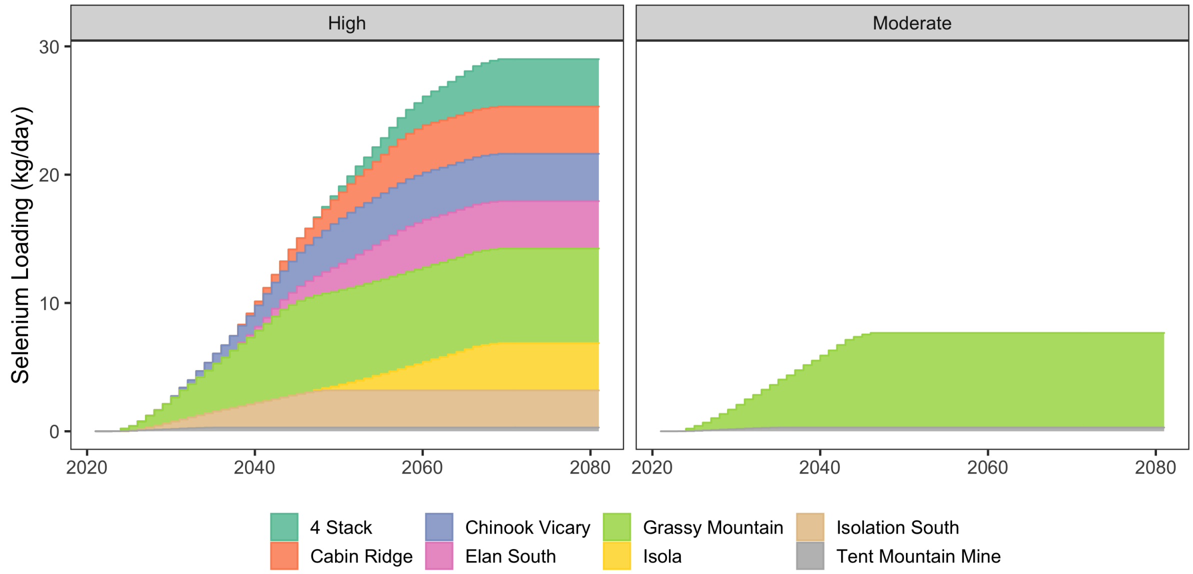

Figure 3.2: Raw mass loading (i.e. no attenuation) by mine under both the Moderate and High scenarios.

Water quality guidelines for selenium are provided in (Table 3.3). These guidelines are based on long-term (chronic) exceedances and were compared against annual average simulated selenium concentrations.

Table 3.3: Published water quality guidelines for long-term selenium concentrations.

Category	Source	Guideline (µg/L)
Aquatic life	Government of Alberta (2018)	2
Drinking water, human	British Columbia (2020)	10
Irrigation	British Columbia (2019)	10
Irrigation - continuous	Government of Alberta (2018)	20
Drinking water, human	Health Canada (2020)	50

4 Results

4.1 Historical Drought Scenarios

Available water volume for two sustained drought scenarios indicate that the proxy drought was more severe than the historical drought (Figure 4.1). The sustained proxy drought had two consecutive years of water deficits followed by a year that was 73% below average conditions followed by another two consecutive water deficit years (Figure 4.1). To compare to the more recent, shorter duration 2000-2001 drought (i.e. most severe drought in the instrumental record; Sauchyn et al., 2016), the available water volume for 2000 was -42,000 dam^3 followed by a water deficit of -251,000 dam^3 in 2001, which then fortunately had 3,510,000 dam^3 in 2002 to replenish water storage in the ORB.

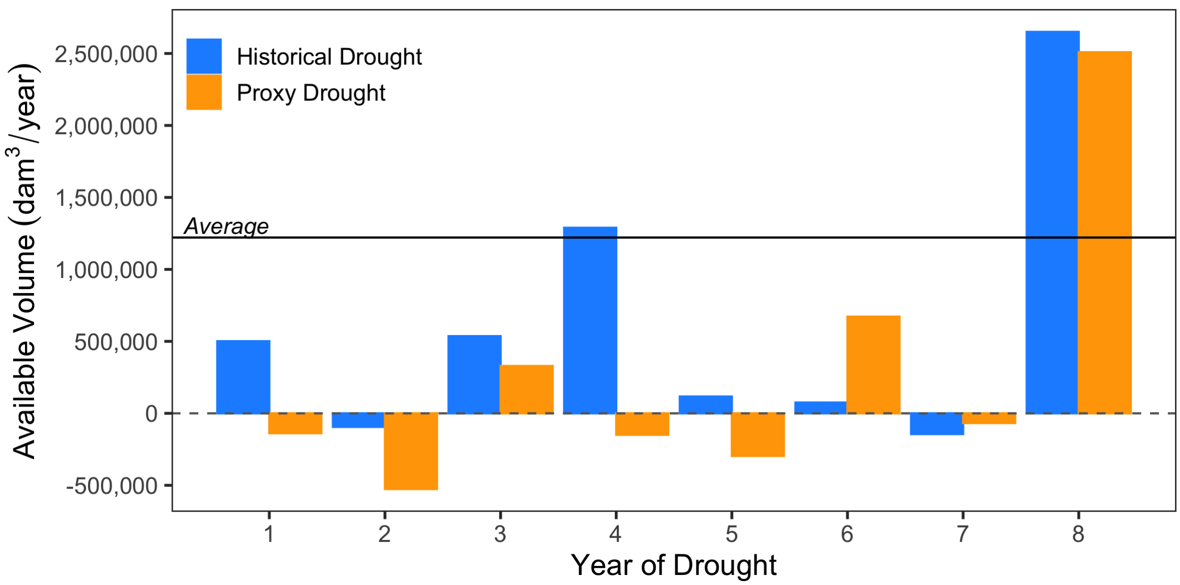

Figure 4.1: Plot of available water volume in the ORB at Lethbridge. Available water volume equals water supply (naturalized Oldman River streamflow near Lethbridge) minus surface licensed use (i.e., allocation minus return flow) for two sustained drought scenarios: historical drought (1935 – 1942) and proxy drought (1717 – 1724). The black line indicates the average conditions (i.e., mean baseline water supply (1961 - 1990) minus surface licensed use).

4.2 Runoff Generation

In the Oldman River, water originates disproportionately from its mountain headwaters (Figure 4.2). Runoff, a measure of streamflow generated, scaled by watershed area, is highest in sub-basins situated along the Continental Divide. In these sub-basins, including the headwaters of the Crowsnest River and Oldman River, as well as major tributaries including Racehorse, Dutch, and Allison Creeks, average runoff ranges from 400 to 500 mm/year. By comparison, lower elevation sub-basins located further east and south produce less than half as much runoff; for example, the Lower Oldman River averages less than 200 mm/year. This dynamic is largely because precipitation is substantially higher at higher elevations and further west in this region. Conversely, evaporation tends to be much higher in the lower elevation prairie located in the southeastern portion of the basin. Proposed open-pit coal mines are located along the western margin and at higher elevations, which means development could potentially affect these high-runoff portions of the ORB that are the most hydrologically productive areas.

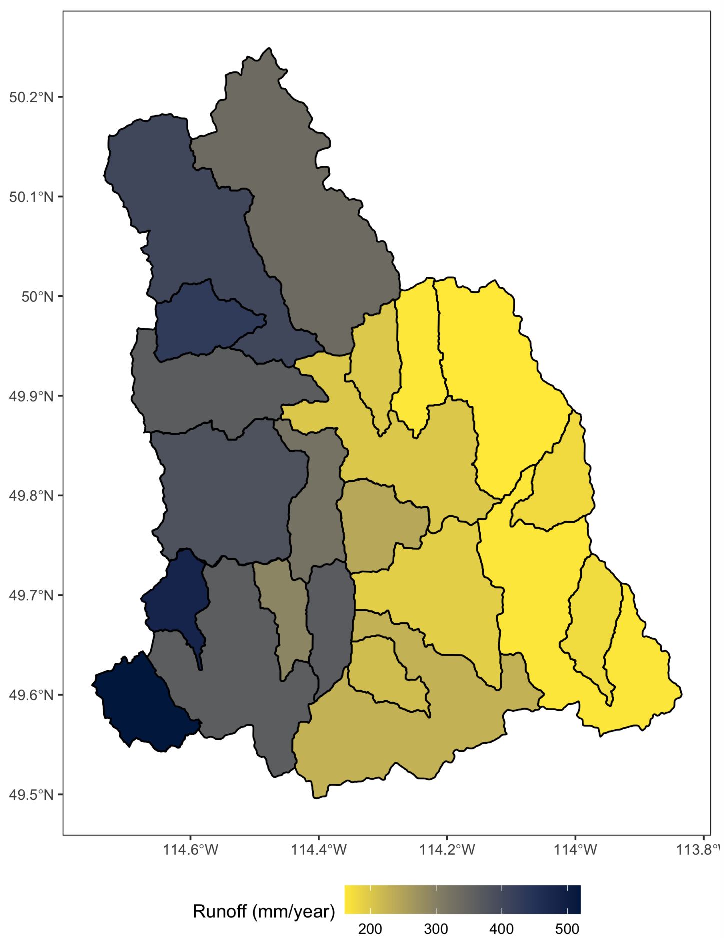

Figure 4.2: Simulated runoff, averaged over the 1990-2019 period by sub-basin.

4.3 Streamflow Timing and Hydrologic Regime

Streamflow in the Oldman River follows a strongly snowmelt-driven pattern (Figure 4.3). Streamflow is exceptionally low during the winter months where most precipitation falls as snow and air temperatures are cold, leading to little snowmelt. During the spring, as air temperatures warm, snowmelt begins, which leads to a rise in streamflow. In addition to snowmelt, most of the annual rainfall falls during the spring, which coincides with peak snowmelt and typically produces the maximum annual streamflow. Once the winter snowpack has been depleted, streamflow declines throughout the summer and coincides with the highest annual rates of evaporation.

Under the climate change scenarios, warmer air temperatures are predicted to result in less winter precipitation falling as snow and an earlier spring snowmelt. Winter rainfall and more frequent snowmelt events could lead to higher winter streamflow. In addition, higher flow in March and April may occur due to snowmelt that starts a several weeks earlier. Conversely, an earlier snowmelt could lead to earlier snowpack depletion and subsequently lower streamflow from June through August. In all cases, greater changes are simulated further into the future (2051-2080 vs. 2021-2050), with marginally greater changes under RCP 8.5.

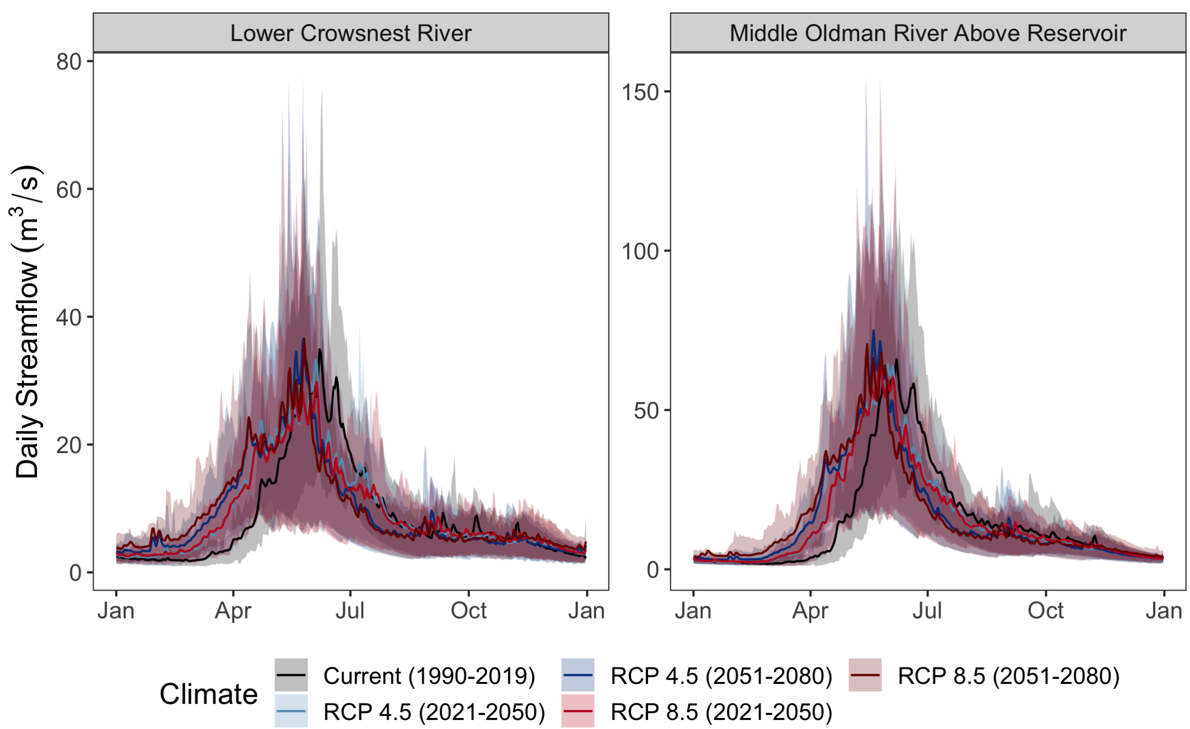

Figure 4.3: Daily streamflow for two major tributaries in the Oldman River under current conditions and future climate change scenarios. Solid lines correspond to the average while shaded areas correspond to 10-90% quantiles.

4.4 Changes in Hydrologic Indicators

4.4.1 Mean Annual Flow

With changes in climate, the hydrologic regime in the ORB is likely to see substantial changes during key times of the year (Figure 4.4). In most sub-basins, the mean

annual flow (i.e. the amount of streamflow produced in a year) is projected to increase. This increase is greatest along the prairie sub-basins, while some headwater sub-basins (Allison Creek and Crowsnest River Above Crowsnest Lake) are projected to see decreases in mean annual flow. At the outlet of the study area (Lower Oldman River Above Reservoir), increases in mean annual flow range from 6% under RCP 8.5 (2021-2050) to 10% under RCP 8.5 (2051-2080). Notably, there is substantial variability in these simulations, with standard errors ranging from 16-33%, suggesting that increased mean annual flow is likely to lead to increased volatility in water supply at an annual timescale.

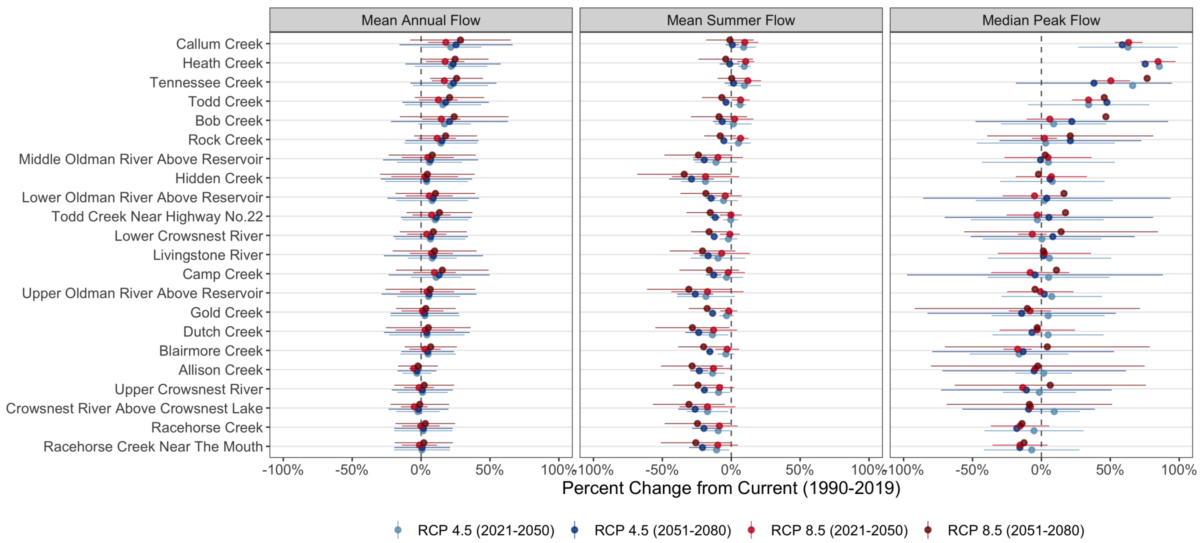

Figure 4.4: Percent change in watershed indicator relative to 1990-2019. Points correspond to average change, while lines represent standard error of the estimate.

4.4.2 Mean Summer Flow

Although mean annual flow is projected to increase in many tributaries and in the Oldman and Crowsnest Rivers, Mean Summer Flow is projected to decrease in most sub-basins in the coming 30 years (2021-2050), while all portions of the study area are projected to experience declining summer flows by the second half of the century (Figure 4.5). Mean Summer Flow at the Lower Oldman River Above Reservoir is projected to decline by 5-7% over the next 30 years, with a decline of 16-20% by 2051-2080. In addition, summer flows are projected to decline substantially in major tributaries in the watershed, including the Lower Crowsnest River (13-17% by 2051-2080) and Livingstone River (17-21% by 2051-2080). Projected declines are greater

than the standard error (in almost all cases), which suggests there is confidence that summer flows are likely to decline in the coming decades.

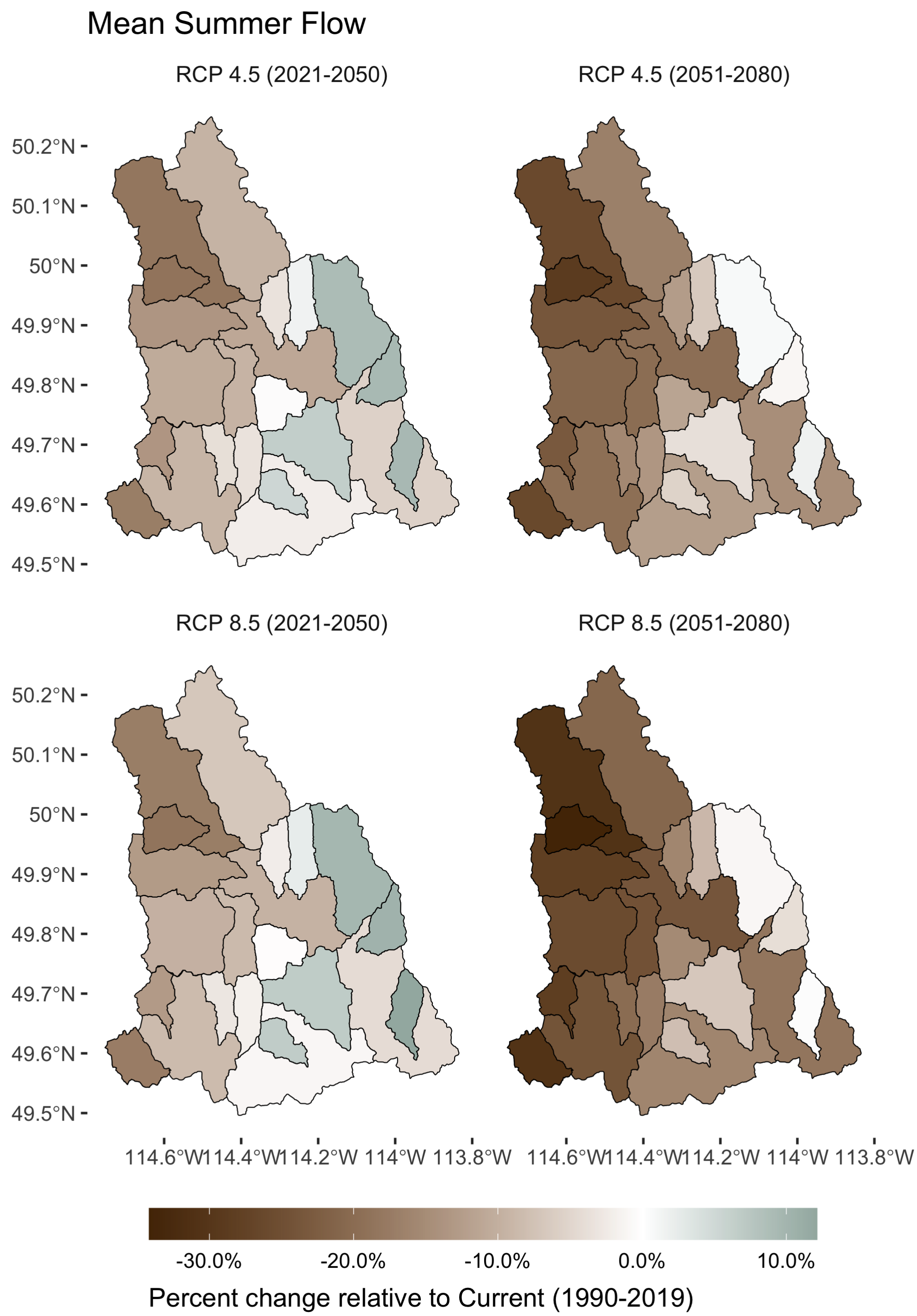

Figure 4.5: Percent change in Mean Summer Flow relative to Current (1990-2019).

4.4.3 Median Peak Flow

Changes in the median peak flow are ambiguous and display a high level of volatility. In the Oldman River, the median peak flow is projected to remain constant under RCP 4.5 and decrease by 11% in 2021-2050 and the change range from -1% (RCP 4.5) to 6% (RCP 8.5) by 2051-2080. Likewise, projected changes in the Crowsnest River range from -11% (RCP 8.5, 2021-2050) to 11% (RCP 8.5 2051-2080). Of note, the standard errors of the estimate range from 10-70% for the Crowsnest River and from 24-112% for the Oldman River, indicating substantial uncertainty and volatility in future median peak flows for the region.

4.5 Mine Development Scenarios

4.5.1 Water Usage

The ORB, as part of the South Saskatchewan River Basin (SSRB), is closed to new water license applications, and therefore any new proponent must obtain a water license through a transfer. While the volume of water allocated cannot increase, water use does not necessarily equal the water allocated. In many cases, license holders only use a fraction of the allocated water; however, this is highly variable between years, industries, and project stage, among other factors. As such, increased mining development has the potential to increase the fraction of allocated water that is used and not returned to the system (i.e. consumptive use).

Scenarios of potential mine development water use suggest consumptive use could affect seasonal streamflow in smaller tributaries. (Figure 4.6). Although potential water allocations are assumed to be seasonally constant, consumptive use would make up a larger proportion of streamflow during low-flow periods of the year, specifically late summer, fall, and winter baseflow. Under the Moderate Scenario, the largest relative water use is in Blairmore Creek, where potential water allocation for the Grassy Mountain Mine exceeds 50% of February and March streamflow approximately once every ten years (consumptive use of approximately 20%), with lowest proportions during the spring and early summer (consumptive use in June exceeding 5% approximately once every ten years). Further downstream, approximately once every ten years consumptive water use would exceed 0.75% of February-March streamflow in the Crowsnest River, 0.3% of streamflow in the Lower Oldman River Above Reservoir, and 0.07% of the streamflow in the Oldman River at Lethbridge.

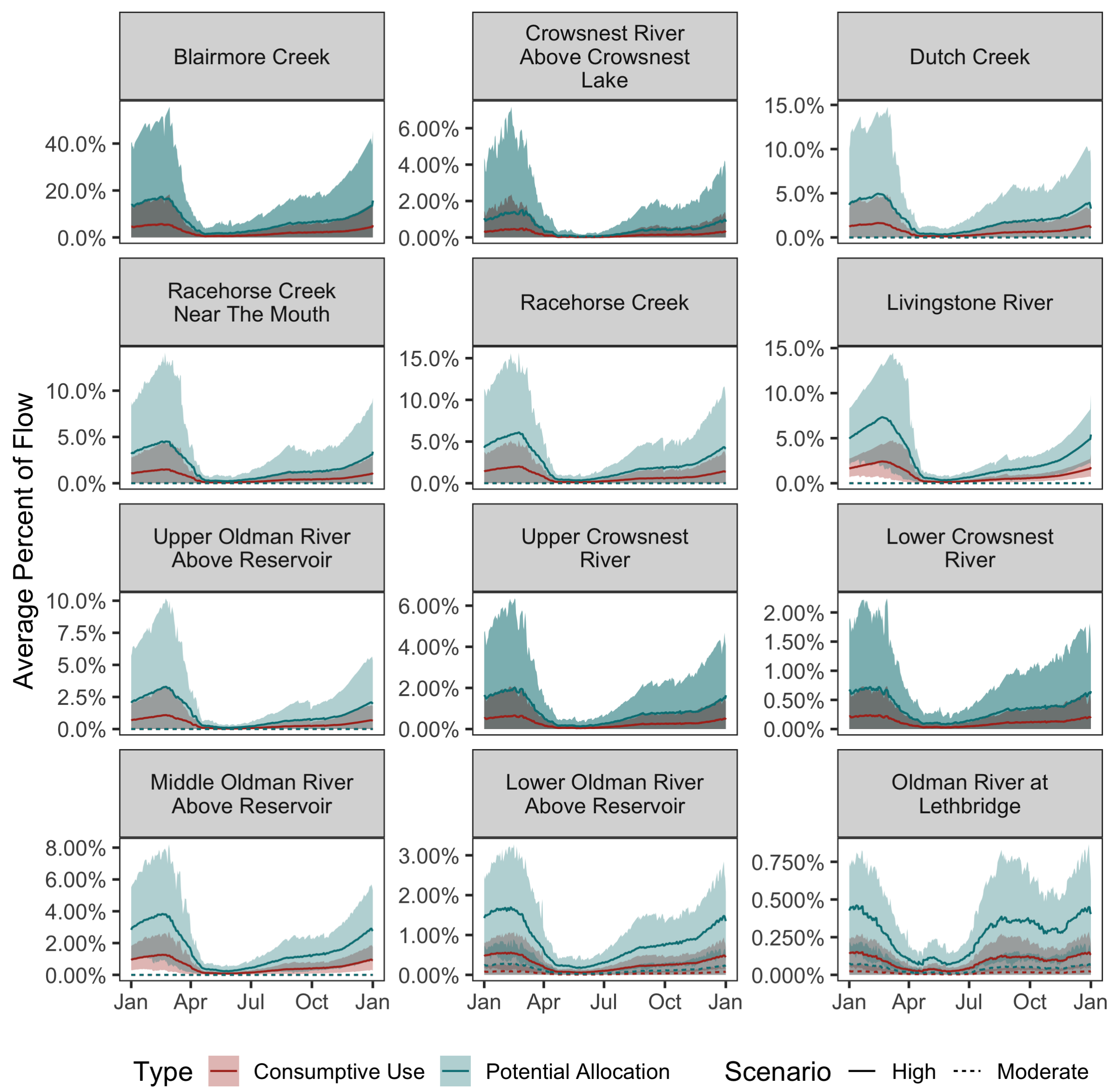

Figure 4.6: Potential allocation and consumed water, as a percent of streamflow under each mining scenario under the averaged future climate change projections. Solid lines represent the average over the 2025-2069 period while the shades lines represent the 10-90% quantiles (i.e. in four out of five years values are within this shaded area).

Under the High Scenario, several major tributaries in the upper Oldman River watershed experience substantial modifications in flow due to consumptive water use. In Dutch Creek, Racehorse Creek, and in the Livingstone River, winter consumptive losses would exceed 5% of streamflow in one out of ten years, while

winter potential allocations could account for upwards of 8% in the Livingstone River in an average year. In the Oldman River, approximately once every ten years consumptive water use would exceed 1% of February-March streamflow above the Oldman Reservoir and 0.3% at Lethbridge. Likewise, under this High mine development scenario, potential allocations to coal mining would account for over 1.5% of winter streamflow in the Oldman River Above Reservoir in an average year over the 2025-2069 period.

4.5.2 Selenium Concentrations

Simulated selenium concentrations in the watershed display a strongly seasonal pattern, with concentrations of four to five times higher in the winter and late-summer/fall than during spring freshet (Figure 4.7). This pattern coincides with the natural seasonal pattern in streamflow, where higher streamflow tends to lead to lower selenium concentrations and spikes in selenium concentrations during low-flow periods. In addition, low flow periods tend to have higher variability in selenium concentrations. Selenium concentrations are higher for all times of the year in the 2051-2080 period compared to the 2021-2050 period. This reflects, in part, the increase in mine development further into the future, as well as a decrease in late summer streamflow under the climate change scenarios further into the 21st century.

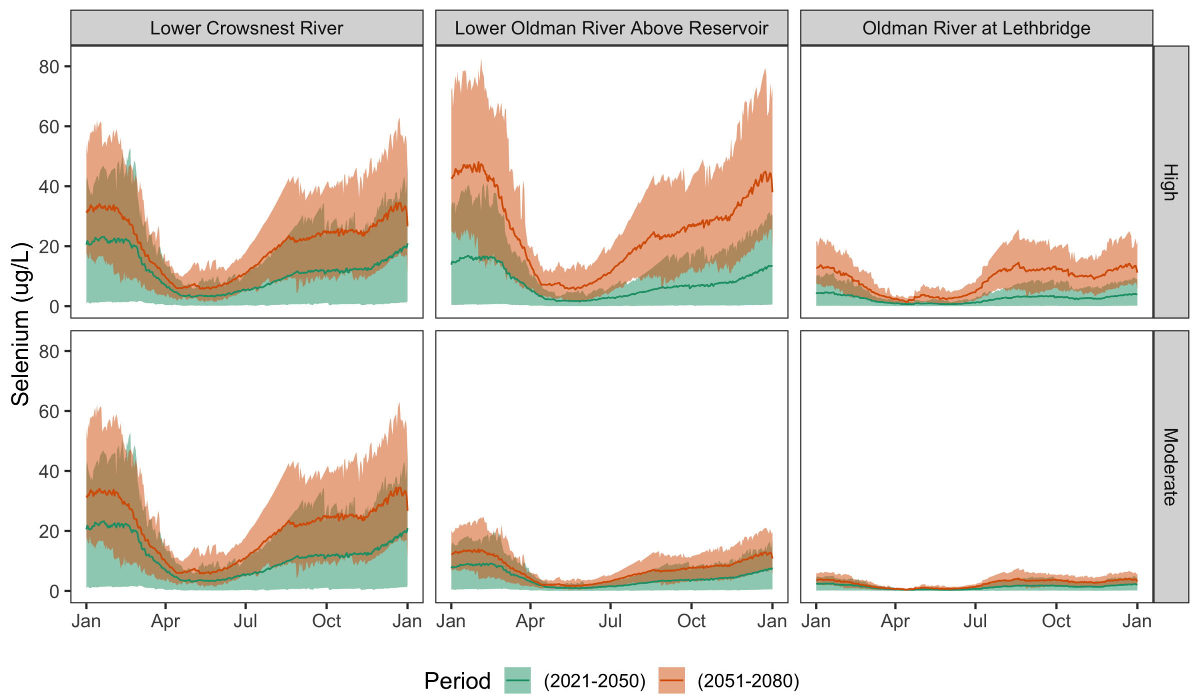

Figure 4.7: Average daily selenium concentrations at major river outlets assuming no attenuation under both mine development scenarios. Solid line corresponds to the average daily value while the shaded area corresponds to the 10 and 90% quantiles (i.e. four out of five years fall within the shaded area).

Annual selenium concentrations are highly dependent on the rate of attenuation achieved (Figure 4.8). Under the Moderate Scenario, average annual selenium concentrations are projected to range from 130-760 µg/L in Blairmore Creek by 2040 with no attenuation, which is approximately 2.5-7.5 times higher than the highest water quality guidelines. Even with moderate attenuation (80%), annual average concentrations would range from 87 to 152 µg/L in the 2040s. We note that these estimates are based on the assumption that all selenium from the Grassy Mountain Mine reports to Blairmore Creek, while its Environmental Assessment (Riversdale Resources Ltd., 2016) assumes some portion of this selenium would instead report to adjacent Gold Creek. Further downstream, annual average concentrations in the Lower Crowsnest River peak above 40 µg/L with no attenuation, 8.2 µg/L with 80% attenuation, and 0.4 µg/L with 99% attenuation.

Under the High Scenario, selenium concentrations in tributaries are projected to require high rates of attenuation to maintain levels below water quality guidelines. With no attenuation, average annual selenium concentrations are projected to exceed

drinking water guidelines (50 µg/L; Health Canada, 2020) in Dutch Creek (150 µg/L), Racehorse Creek and the Livingstone River (130 µg/L), and the Lower Oldman River (50 µg/L), while others could exceed selenium concentration guidelines for aquatic health (2 µg/L; Government of Alberta, 2018) or continuous irrigation (20 µg/L; Government of Alberta, 2018) like the Crowsnest River (40 µg/L), and the Oldman River at Lethbridge (20 µg/L). With an attenuation of 80%, average annual selenium concentrations are projected to exceed 25 µg/L in the Livingstone River, while the Oldman River is projected to have annual average concentrations peak at 11 µg/L above the Reservoir and reach 4 µg/L at Lethbridge.

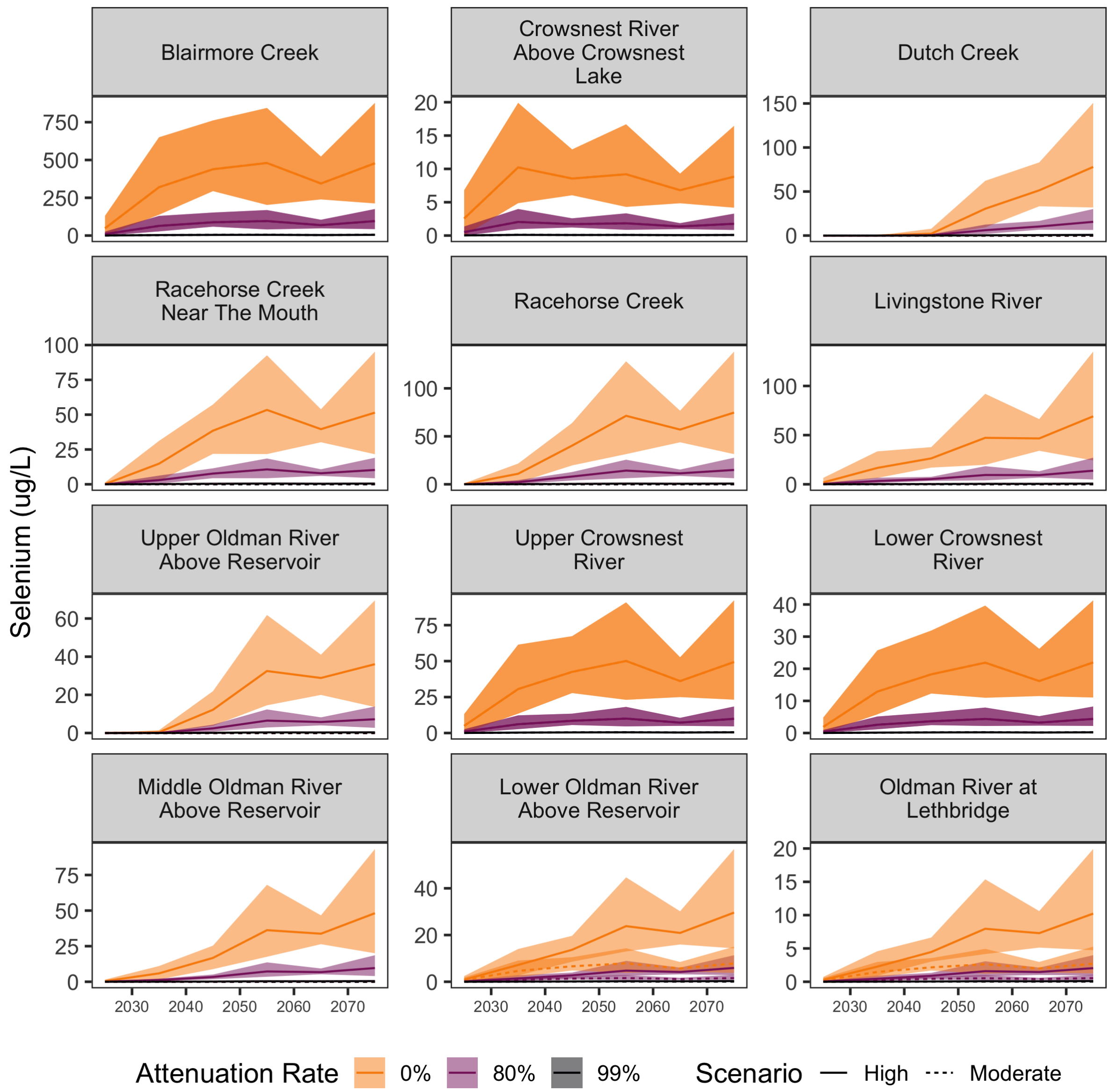

Figure 4.8: Average annual selenium concentrations at all affected sub-basin outlets under both mine development scenarios and three attenuation rates. Solid line corresponds to the decadal average value while the shaded area corresponds to the maximum and minimum annual averages for the decade.

Estimated selenium concentrations in affected tributaries and on larger rivers in the upper ORB, absent any attenuation, are substantially above most water quality guidelines (Table 4.1). As such, use of a range of effective mitigation approaches would be required to maintain adequate water quality in the watershed if mine development were to take place. For instance, in the Lower Crowsnest River, average

annual selenium concentrations, without attenuation, peak above 40 µg/L; an attenuation rate of at least 52% would be required to maintain selenium concentrations below Government of Alberta irrigation thresholds, an attenuation rate of approximately 76% would be required to maintain the British Columbia human drinking water guideline, and an attenuation rate of 95% would be required to achieve the Alberta aquatic life guideline.

Under the High Scenario, average annual selenium concentrations, without attenuation, peak at 57 µg/L on the Oldman River above Reservoir; an attenuation rate of at least 65% would be required to maintain selenium concentrations below Government of Alberta irrigation thresholds, an attenuation rate of 83% would be required to reach the British Columbia human drinking water guideline, and an attenuation rate of 97% would be required to not exceed the Alberta aquatic life guideline. At smaller tributaries, such as Blairmore Creek, Dutch Creek, Racehorse Creek, and the Livingstone River, attenuation rates above 90% would be required in most cases to ensure most water quality guidelines are not exceeded on an annual average.

Table 4.1: Minimum selenium attenuation rate required to meet various water quality guidelines at selected affected waterways in the Oldman River watershed under the High mine development scenario.

Site	**Peak Annual Average Concentration (µg/L)**	**BC - Drinking Water**	**BC - Irrigation**	**Canada - Drinking Water**	**GoA - Aquatic Life**	**GoA - Irrigation (continuous)**
Blairmore Creek	878	99%	99%	94%	100%	98%
Dutch Creek	151	93%	93%	67%	99%	87%
Racehorse Creek	138	93%	93%	64%	99%	86%
Livingstone River	135	93%	93%	63%	99%	85%
Racehorse Creek Near The Mouth	95	90%	90%	48%	98%	79%
Middle Oldman River Above Reservoir	93	89%	89%	46%	98%	79%
Upper Crowsnest River	92	89%	89%	46%	98%	78%
Upper Oldman River Above Reservoir	70	86%	86%	28%	97%	71%
Lower Oldman River Above Reservoir	57	82%	82%	12%	96%	65%
Lower Crowsnest River	41	76%	76%	0%	95%	52%
Crowsnest River Above Crowsnest Lake	20	50%	50%	0%	90%	0%
Oldman River at Lethbridge	20	50%	50%	0%	90%	0%

5 Discussion

For the ORB, the major future challenge in terms of water supply is drought, which is a normal part of the climate for semi-arid regions (Wheaton et al., 2008). To evaluate the probability of severe drought and the stress on future water supply, three main factors must be considered: paleo-climate evidence (i.e. historical drought pattern), enhanced drought probability with climate change (i.e., hydrological modelling), and increasing demand for good quality water. In addition, due to potential future open-pit coal mine development in the ORB, water quality can be degraded by both reductions in flow, due to changing hydroclimatic conditions as well as increases in consumptive water use, and selenium loading from coal processing.

5.1 Water Supply

Paleo-climate evidence from tree-ring reconstructions provide a broader perspective on the variability in streamflow that assesses the reliability of the water supply under a wider range of flows than recorded by a gauge. Our analysis suggests that the sustained proxy drought (1717 – 1724) was much more severe than the sustained historical drought of the 1930s and would have consequences on the water supply in the ORB needed by irrigators and downstream users. In addition, the senior water licenses in Alberta were granted to the irrigation districts during a period of climate on the Canadian prairies when water supply availability was some of the highest over the last millennium based on tree-ring reconstructions (1870 – 1920; Fleming and Sauchyn, 2013).

The initial widespread settlement of people (1890s to 1910s) converted native prairie to agricultural cropland and the precedents for water allocation and use were established (Fleming and Sauchyn, 2013). It is also possible that observations of streamflow conditions during this period may have led to water policy decisions and practices in Alberta that may not be consistent with the climate conditions that, from a longer-term perspective (i.e. paleohydrological records), are not normally encountered in the region (Fleming and Sauchyn, 2013). These circumstances are potential analogous to the Colorado River Compact (i.e., 1922 agreement that governs allocations of water rights) that was found to lead to a water supply overallocation because water policy decisions were made during a period revealed

from paleo-climate investigations to be of unusually high flow (Stockton & Jacoby, 1976; Meko et al., 1995).

The paleohydrological record of water supply in the ORB during sustained drought scenarios suggest water needs would exceed supply for more than two consecutive years and subsequent low supply years would not be adequate to fill water storage in the basin should these conditions occur. In other words, water deficits for more than two years could not be sufficiently mitigated by water storage held in reservoirs to offset low flows (Sauchyn et al., 2016) and would also challenge the provision for environmental instream flows (Rood and Vandersteen, 2010). In a more recent example, the drought of 2000 – 2001 was the most severe drought in the instrumental record, and collaborative sharing agreements among irrigation users emerged in 2001 (i.e., senior versus junior license holders); however, many agreed that had the drought continued for one or more additional years the agreement would not have been an effective response for the water users, particularly junior license holders (Sauchyn et al., 2016). For example, if heavy spring rains had not occurred in 2002, all licenses after 1950 in the St. Mary, Belly and Waterton River sub-basins would have had their supplies cut-off (Rood and Vandersteen, 2010). Even more, if only modest spring rains had occurred, recent licenses (post 1994) would have been cut off, which included a large food-processing plant, 12 municipal water supplies, and livestock watering (Rood and Vandersteen, 2010). The drought conditions of 2000 – 2001 had major socioeconomic consequences, but from a paleo-climate context the 20th century had frequent, short duration droughts and contrasts the 18th and 19th centuries that were characterized by sustained drier conditions including prolonged drought (Sauchyn et al., 2003). These sustained historical droughts of the past are likely to reoccur in the future, particularly in a warmer climate.

Most global climate models project increased drying in the continental interior in the summer, and subsequently a greater risk of droughts for the 21st century (Wheaton et al., 2008). Most definitions of drought refer to water shortages caused by lack of precipitation (Wilhite, 2011); however, research has suggested that more recent droughts in large United States river basins may have increased drought severity due to the increasing air temperatures from climate warming (Martin et al., 2020). Specifically, the recent drought in the Upper Missouri River Basin (2000 – 2010) was likely more severe than any drought recorded in the instrumental record and a 1,200 year reconstructed proxy record suggests that the occurrence of extreme heat, higher evapotranspiration, and associated low-flow conditions across the basin since the 1980s onward has led to increased drought severities compared to the last 12 centuries (Martin et al., 2020). In addition to the potential effects of climate change,

climate anomalies such as ENSO, PDO, and the North American Oscillation (NAO) may lead to significant changes in streamflow in western Canada and affect inter-annual water supply (Whitfield et al., 2010; Newton et al., 2014; St. Jacques et al., 2012; Fleming and Sauchyn et al., 2013). For example, model simulations suggest that water allocation deficits are predicted to be more severely affected with a warming climate and an active El Niño episode, while less so with a La Niña anomaly of the ENSO (Islam and Gan, 2016). Therefore, hydro-climatic variability (i.e. teleconnections between ocean-atmosphere oscillations and the hydrologic regime) in addition to future warming (i.e., increased regional aridity) is anticipated to cause more severe droughts and could be superimposed on a recurrence of a prolonged drying event seen in the historical proxy record.

Simulations of climate change scenarios in the upper ORB suggest warmer air temperatures will likely lead to less winter precipitation falling as snow and earlier spring snowmelt, which subsequently could result in higher winter baseflow and less summer (June – August) streamflow. The hydrological regime of the ORB will likely become increasingly sensitive to the timing and frequency of rainfall events, and the storage reservoirs in the basin will have less of a buffer from the later melt of a larger snowpack. The climate change scenarios used in this study were median projections from a multi-model ensemble for two emissions pathways (RCP 4.5 and RCP 8.5). These scenarios represent the “middle-of-the-road” climate projections. As such, they may be our best guess at average future conditions, but likely underestimate the potential of extreme climate events, such as prolonged droughts or floods. This dynamic is important given the effects of both water use and selenium concentrations are sensitive to the hydroclimatic conditions at the time. Prolonged drought conditions, for instance, could lead to significant degradation of water quality beyond what is estimated here. Further work could use this framework to provide a more robust risk analysis using a suite of climate change scenarios.

5.2 Water Quality

Simulations of mine development suggest that selenium concentrations will exceed water quality guidelines without substantial mitigation measures. Headwater tributaries are particularly sensitive to water quality degradation since they bear the full brunt of selenium loading but contain relatively little streamflow to aid in dilution. Likewise, water use from mining operations is likely to be largely concentrated in these same headwater sub-basins, where they make up a greater portion of streamflow, and would exacerbate water quality concerns.

This study considered selenium concentration in exceedance of water quality guidelines only on an annual timescale. This study choice was made given the relative uncertainty in mine development plans, potential seasonal patterns in selenium loading, and uncertainty in the precise definition of “long-term” or “chronic” in relation to water quality guidelines. Simulations from the hydrological model at a daily timestep show that selenium concentrations can vary substantially throughout the year, and concentrations during low flow periods can be several times greater than the annual average. As such, we emphasize that the water quality guideline exceedances presented here are based on annual averages and that it is likely that seasonal effects will lead to substantially higher selenium concentrations during low flow periods. This could have important effects on the suitability of a water source for a variety of uses, but the specific effect is beyond the scope of this study.

While this study considered the consumptive water use and selenium loading in two mine development scenarios, the model did not contemplate how the physical footprint of the mine would impact streamflow. Given that most of open-pit mines have a large physical footprint, their development will substantially alter the landscape. For instance, mine development will remove tree-cover, which can have important hydrological implications; less canopy interception, faster and earlier spring snowmelt, and possibly higher evaporation rates. In addition, most mines proposed are in higher elevations and in areas with greater precipitation; both factors that increase the impact of land cover change. Little is understood about the hydrologic response to coal mining, with variable responses depending on a wide range of factors like topographic change, water management, and geographic setting. This study does not contemplate how mines will manage their on-site water. Diversions, storing/settling ponds, and/or delayed releases of water could affect downstream hydrology. Further research into the physical effect of mine development on hydrological processes, including changing topography, vegetation and soil characteristics, would provide valuable information and improve our understanding of changes in streamflow magnitude and timing due to mine development.

6 Conclusions

This project provides a broad perspective on the variability of water resources in the Oldman River basin and outlines the potential increase in risks to sustainable water management in the coming decades. The paleohydrological analysis used sustained drought scenarios derived from tree-ring reconstructions of streamflow that provided

a historical context for the variability of water supply that has and could reoccur in the ORB. A hydrological model of the upper Oldman River basin was developed in order to simulate streamflow for tributaries and the mainstream Oldman River under a recent historical period (1989-2019) and to estimate streamflow under two future climate change scenarios (RCP 4.5 and RCP 8.5). The model integrates water use and selenium mass loading associated with two future mine development scenarios to estimate changes to water supply and quality in the watershed. The change in water quantity due to water use and climate change is summarized using three hydroclimatic indicators to highlight periods of the year when water quantity is of heightened importance. Concentrations of selenium at all sub-basin outlets were simulated within the hydrological model and are compared against water quality guidelines.

Findings from this study are as follows:

- Streamflow in the Oldman River basin originates disproportionately from its mountain headwaters, while by comparison, lower elevation sub-basins located further east and south produce less than half as much runoff. Mine development is primarily located in these hydrologically productive areas.
- Streamflow in the Oldman River follows a strongly snowmelt-driven pattern with high flows coinciding with peak snowmelt and greater rainfall in the spring, and low flows during the late summer and winter months.
- Instrumental records do not show the full range of variability in the Oldman River hydrologic regime and water resource managers must consider less certainty and stationarity in future water supplies, particularly in a basin where water supply challenges are likely based on the longer-term paleohydrological record.
- Prolonged droughts leading to water supply deficits have occurred in the historical proxy record and are likely to occur in the future, especially in a warming climate.
- Under future climate change scenarios, warmer air temperatures are likely to lead to less winter precipitation falling as snow, and earlier spring snowmelt. These factors lead to higher winter streamflow, an earlier spring peak, and substantially reduced late season flows.
- In most sub-basins, the mean annual flow (i.e. the amount of streamflow produced in a year) is projected to increase; however, this increase is greatest

along the prairie sub-basins, while some headwaters sub-basins are projected to see decreases in mean annual flow, in addition to increased volatility in water supply at an annual timescale.

- Mean Summer Flow is projected to decrease in most sub-basins in the coming 30 years (2021-2050), while all portions of the upper Oldman River watershed are projected to experience declining summer flows by the second half of the century.
- Consumptive water use projected from mine development scenarios is relatively small at the scale of the Oldman River watershed, but is seasonally significant and is a substantial proportion of winter flows in major tributaries, where many mines are likely to be located. There is additional risk of greater reductions in streamflow if a low-flow year coincides with peak mine development and/or if consumptive water use is higher than currently estimated, since potential allocations are approximately three times greater.
- Estimated selenium concentrations in affected tributaries and on larger rivers in the upper Oldman River watershed, absent any attenuation, are substantially above most water quality guidelines. A strong reliance on mitigation technologies (i.e. selenium attenuation) would be required to maintain adequate water quality in the watershed if mine development were to take place.

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8 Appendix A: Hydrological Model Details

8.1 Oldman River Hydrological Model

Streamflow and other hydroclimatic variables in upper Oldman River watershed are simulated using a process-based hydrological model. This model is an adapted version of the HBV-EC hydrological model (Bergström, 1992), emulated within the Raven Hydrological Modelling Framework version 3.0 (Craig et al., 2020). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep. The model integrates weather data (daily minimum and maximum air temperature and precipitation) and landscape attributes (land cover, elevation, soil types) in order to simulate major hydrological processes including canopy interception, snow accumulation and melt, evaporation, soil infiltration, percolation, interflow, baseflow, as well as runoff. Contaminant loading and transport (i.e. selenium loading and concentration estimates) is simulated within Raven using built-in functionality to calculate sub-basin concentrations based on supplied mass loadings. Downstream transport of selenium is simulated using Raven's constituent transport algorithms which incorporate sub-basin routing and travel times based on sub-basin properties, including slope, manning's roughness, and length (Craig et al., 2020).

8.1.1 Data Sources

8.1.1.1 Landscape

The upper Oldman River was discretized into fundamental watershed units for input into the hydrological model. The area within each unit is assumed to have uniform hydrologic behaviour and is summarised with a land cover type, soil type, elevation, aspect, and slope. Land cover for the area was obtained from the ABMI wall-to-wall 2010 Land Cover Inventory (ABMI, 2013) and reclassified it into 8 classes: Alpine, Coniferous, Deciduous, Developed (i.e. bare or urban cover), Glacier, Grassland, Lake, and Shrubland. Soil type was tied to whether the land cover was vegetation type. Elevation, slope, and aspect were obtained using the Canadian Digital Elevation Data digital elevation model (Natural Resources Canada, 2016).

8.1.1.2 Weather and Climate

In order to run the hydrological model, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data were collected from DayMet (Thornton et al., 2020) using the Single Pixel Extraction Tool to obtain observations from 1980-2019 for at a 0.15 degree resolution. Since DayMet data are based on a 1x1 km grid cell, reference elevations are obtained for each data point and are used to correct observations to fundamental watershed unit elevations using specified lapse rates within the hydrological model.

Future climate change scenarios were generated from statistically downscaled climate scenarios obtained from Environment and Climate Change Canada (ECCC, 2021) under two representative concentration pathways (RCPs). RCP 4.5 corresponds to a scenario where carbon emissions stabilize by 2040, while RCP 8.5 represents a scenario with minimal greenhouse gas emission mitigation. These scenarios applied the median projection from an equal-weighting ensemble forecast of 24 General Circulation Models (GCM) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) from 2021-2100. Projections among climate models can vary because of differences in their underlying representation of earth system processes. Thus, the use of a multi-model ensemble approach has been demonstrated in recent scientific literature to likely provide better projected climate change information (Zhang et al., 2019, ECCC, 2021).

Daily future weather was generated by first bias-correcting projected climate values by calculating the change between simulated future air temperature and precipitation and historical (simulated). Each future month and year was then matched with a proxy month from the baseline (observed) period. These scaling factors for each month and year (i.e. fractional difference in precipitation and absolute difference in air temperature between the proxy and scenario) were then used these to correct the daily observed record for each climate scenario.

8.1.2 Model Calibration and Performance

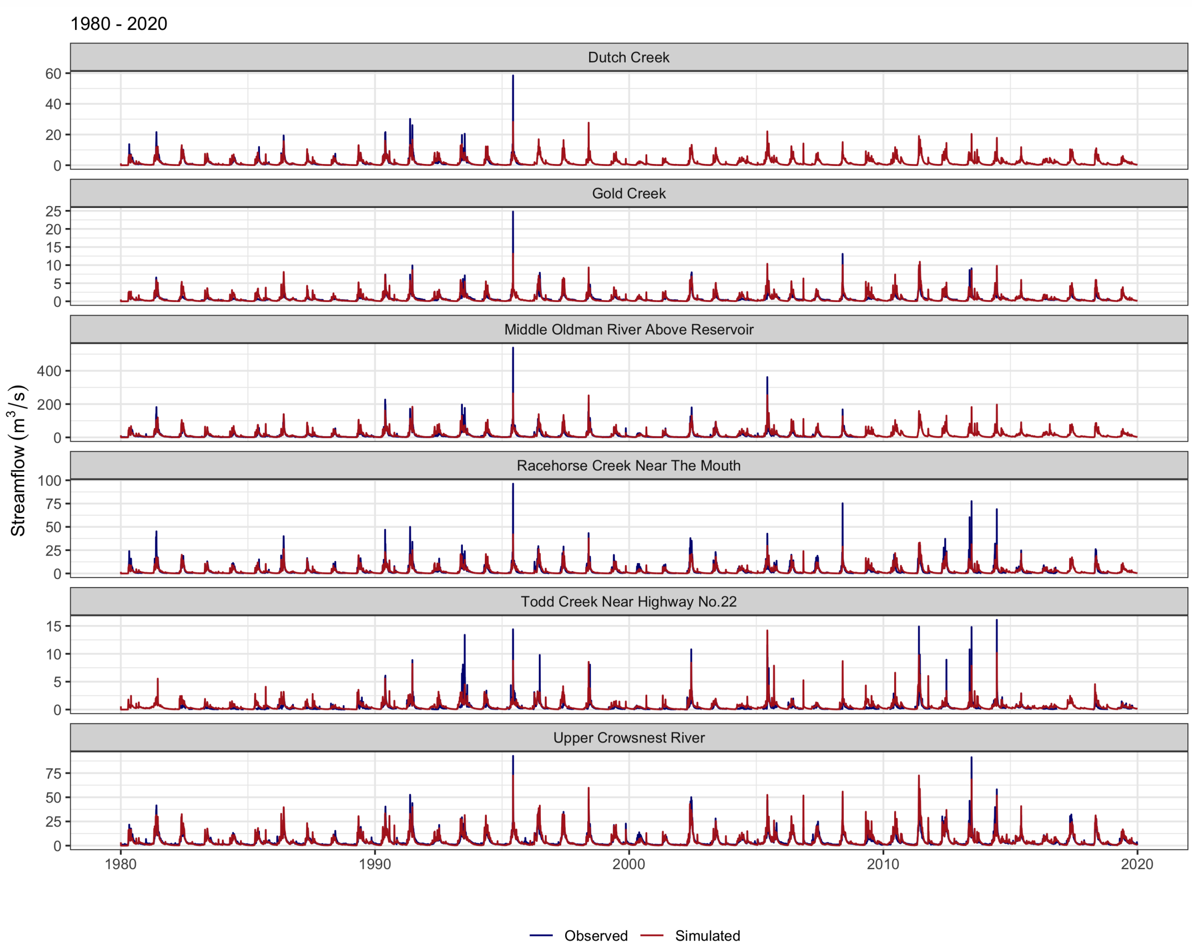
In order to ensure the hydrological model properly and accurately simulates hydrologic processes, model parameters were calibrated to hydroclimatic observations in the watershed. Air temperature, precipitation, and snow simulations were verified against local weather stations and snow surveys. Streamflow was calibrated and verified against Water Survey of Canada hydrometric stations on the

Oldman River and Crowsnest River as well as major tributaries Racehorse Creek and Dutch Creek (WSC, 2021).

Overall, the model displays good performance at reproducing daily streamflow as well as accurately reproducing air temperature, precipitation, and the winter snowpack across the watershed. Qualitatively, the model does a good job at reproducing the timing and magnitude of spring runoff, indicating that snowmelt timing and rate is generally well reproduced. In addition, winter streamflow, only available for verification at the Oldman River hydrometric site, is well reproduced. In addition, streamflow during the late summer and fall period (August-November) is well represented, but is slightly over-estimated, particularly in Racehorse Creek. Overall, the inter-annual and daily variability in flow is well reproduced, following the character of the observed hydrographs.

Table 8.1: Daily streamflow performance statistics for the calibration (2000-2008 for Oldman River Near Waldron's Corner/Middle Oldman River Above Reservoir) and verification periods (entire record except on Oldman River). *Note: NSE is the Nash-Sutcliffe Efficiency, KGE is the Kling-Gupta Efficiency; both ranging from negative infinity to 1 (perfect simulation), and PBIAS is the percent bias.*

Site	Period	NSE	KGE	PBIAS
Dutch Creek	Verification	0.70	0.67	6.2
Gold Creek	Verification	0.46	0.66	14.0
Middle Oldman River Above Reservoir	Calibration	0.85	0.82	16.3
Middle Oldman River Above Reservoir	Verification	0.78	0.81	10.5
Racehorse Creek Near The Mouth	Verification	0.72	0.71	0.9
Todd Creek Near Highway No.22	Verification	0.42	0.46	46.0
Upper Crowsnest River	Verification	0.81	0.89	0.4



8.1.3 Model Uncertainty and Limitations

Overall, the hydrological model shows good performance in reproducing daily streamflow at the hydrometric gauges. The model is able to reproduce the timing on peak flows as well as the variability in daily and seasonal streamflow. Model performance is best at major river outlets (Middle Oldman River and Crowsnest River and has weakest performance statistics in arid, more easterly and prairie landscape sub-basins such as Todd Creek. The model under-simulates the amount of water in the Crowsnest River system (but not in tributary Gold Creek) and modestly over-estimates streamflow in the upper Oldman River River. In addition, verification of weather and snowpack information suggest the model may not fully represent the magnitude of the precipitation gradient in the region. Snow water equivalent (SWE) is underestimated along the Continental Divide at snow pillows Lost Creek and Allison Pass, while precipitation is over-estimated at Livingstone Lookout weather station.

This dynamic may only have minimal effects on model performance at WSC hydrometric gauges since their catchment areas cover both extremes of this gradient. However, this model weakness may underestimate the differences in hydrologic regime between sub-basins in the east and those in the west, along the Continental Divide.

While the hydrological model does show discernible weaknesses, overall, it shows good performance reproducing streamflow, and in particular is able to reproduce streamflow indicators with comparable accuracy. In addition, the model reproduces air temperature, precipitation, and snow water equivalent at most verification sites relatively well. Likewise, vegetation parameters have been imposed from remotely sensed imagery and field studies in similar environments, reducing model flexibility and providing confidence that the model has comparably strong process-representation, and is producing accurate results for the right reasons. These findings suggest that the model is an appropriate tool to identify relative changes in magnitude of forest disturbance and to identify areas within the study area of increased hydrological alteration and sensitivity.

9 Appendix B: Mine Development Assumptions

9.1 Overall approach

Selenium (Se) loads for simulated coal mines were based on coefficients relating annual Se loads to volume of coal waste rock. These coefficients are reported in documents available through the Elk Valley Water Quality Plan (SRK, 2014) and through Benga Mining Ltd.'s Updated Environmental Impact Assessment for the Grassy Mountain Coal Project (SRK, 2016). The primary justification for these coefficients and approach is the observed relationship between Se concentrations in the Elk River (Figure 9.1) and the deposition of coal waste rock, which implies that Se release can be predicted from waste-rock volumes generated by future mining operations (SRK 2014).

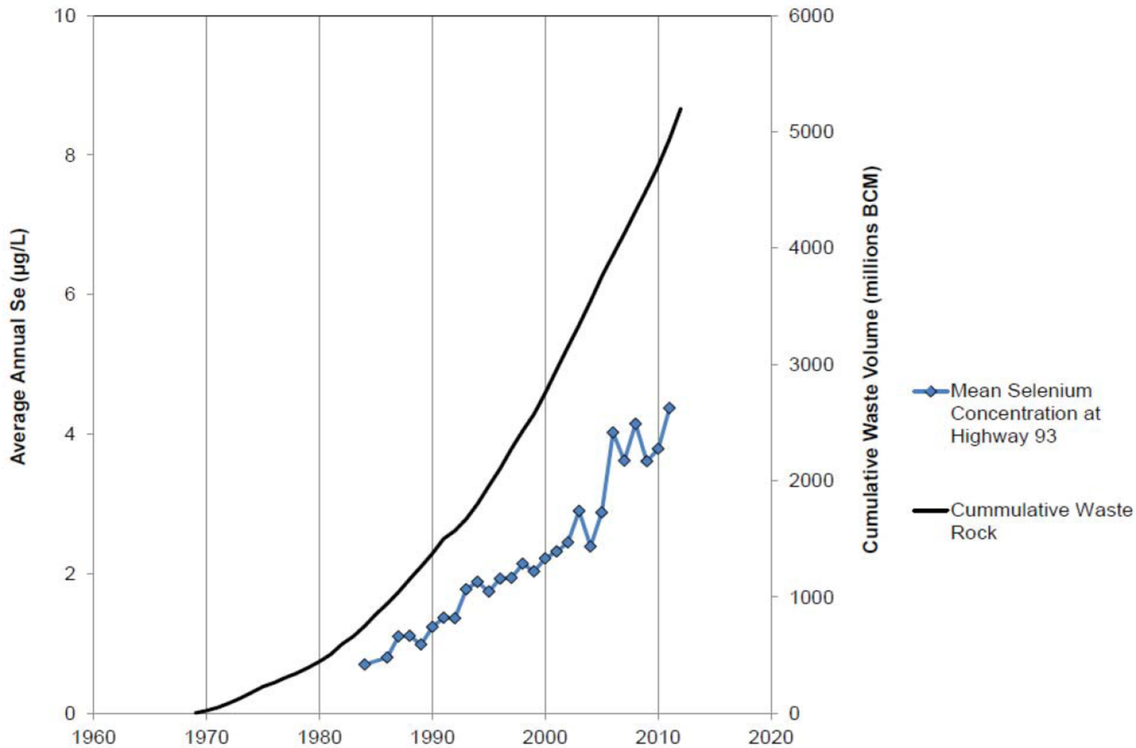


Figure 9.1: Observed relationship between Se concentrations and waste rock volumes in the Elk River, B.C. (SRK 2014).

Using the coefficients published for the Elk Valley and Grassy Mountain, the annual load of Se (L_{Se}, in mg/year) from a mine can be estimated as:

$$L_{Se} = V_{rock} R_{Se}$$

where V_{rock} is the cumulative volume of coal waste rock deposited (in bank cubic metres, or BCM), and R_{Se} is the generation rate of Se from waste rock in mg/m^3/yr (SRK 2014). The rate coefficients for Se generation vary by location; Table 9.1 provides rates used in this study. SRK 2014 and 2016 provide higher rates of Se generation for each mine or location, described either as "95% upper confidence limit" (SRK 2014) or "worst case" (SRK 2016). These rates were not used in this study, as they are not required to demonstrate Se effects on downstream surface water. SRK 2016 also provides different (higher) Se-generation rates for coal co-disposed with coarse coal rejects, but these rates were not used in this study, as we have no information on the details of waste disposal.

Table 9.1: Se generation rates used by mine.

Mine	Se generation rate (mg/m^3/year)
Grassy Mountain	3.20
Tent Mountain	0.55
All others	1.60

Selenium generation rates for Grassy Mountain were obtained from SRK (2016). The rate for Coal Mountain was used as Tent Mountain is directly north of Coal Mountain and so assumed to have similar Se generation rates, which are lower than those generally observed from the Mist Mountain formation in the Elk Valley (SRK, 2014). The selenium generation rates for all other mines use the generic rate given by SRK for all mines in the Elk Valley other than Coal Mountain.

9.1.1 Simulating waste-rock deposition

Simulating Se loads therefore required simulation of generation of waste rock by mine site over time. The basis of this simulation was published values for waste-rock deposition from Grassy Mountain (SRK 2016) and Tent Mountain (SRK 2020). Table 9.2 provides a summary of these simulations, based on the following assumptions:

- **Timeframe**: Grassy Mountain projected a schedule of 23 years of waste-rock deposition commencing in 2019. This timeframe was advanced in our simulations to begin in 2024 as the mine has not yet been approved or commenced construction. Tent Mountain projected a schedule of 14 years of waste-rock deposition commencing in 2021; this was advanced to 2023 for similar reasons. All other mines were based on Grassy Mountain's deposition schedule, but shifted forward in time.

- **Waste-rock volumes**: volumes for Grassy Mountain and Tent Mountain were taken directly from their technical reports (SRK 2016 and 2020, respectively). For all other mines, volumes were based on the assumption that these mines would have a similar size, lifespan, production, and waste-rock deposition as Grassy Mountain. Isolation South was modelled as having less waste-rock deposition for an operation similar to Grassy Mountain, as Atrum Coal (2020) claims a lower stripping ratio (BCM waste rock: tonnes clean coal) than Grassy Mountain or the Elk Valley operations. The overall schedule and sequencing of cumulative waste-rock deposition across all mines in the high-development scenario was adjusted

to be similar, but somewhat lower than, the historical trajectory of mine development in the Elk Valley (Figure 9.1), with 5908.9 million BCM of waste rock deposited over the 50-year simulation (Figure **??**). This schedule is meant to recognize the lead time required to get projects approved and constructed, and a possible future transition away from metallurgical coal in the steel-making industry.

Table 9.2: Simulation of waste-rock volumes by mine.

Mine	Timeframe	Source	Cumulative simulated waste-rock volumes (millions BCM)
Grassy Mountain	2024-2046	SRK 2016	842.2
Tent Mountain	2023-2036	SRK 2020	194.5
Isolation South	2026-2048	SRK 2016	661.2
Elan South	2038-2060	SRK 2016	842.2
Chinook Vicary	2030-2052	SRK 2016	842.2
Cabin Ridge	2038-2060	SRK 2016	842.2
Isola	2047-2069	SRK 2016	842.2
4-Stack	2047-2069	SRK 2016	842.2

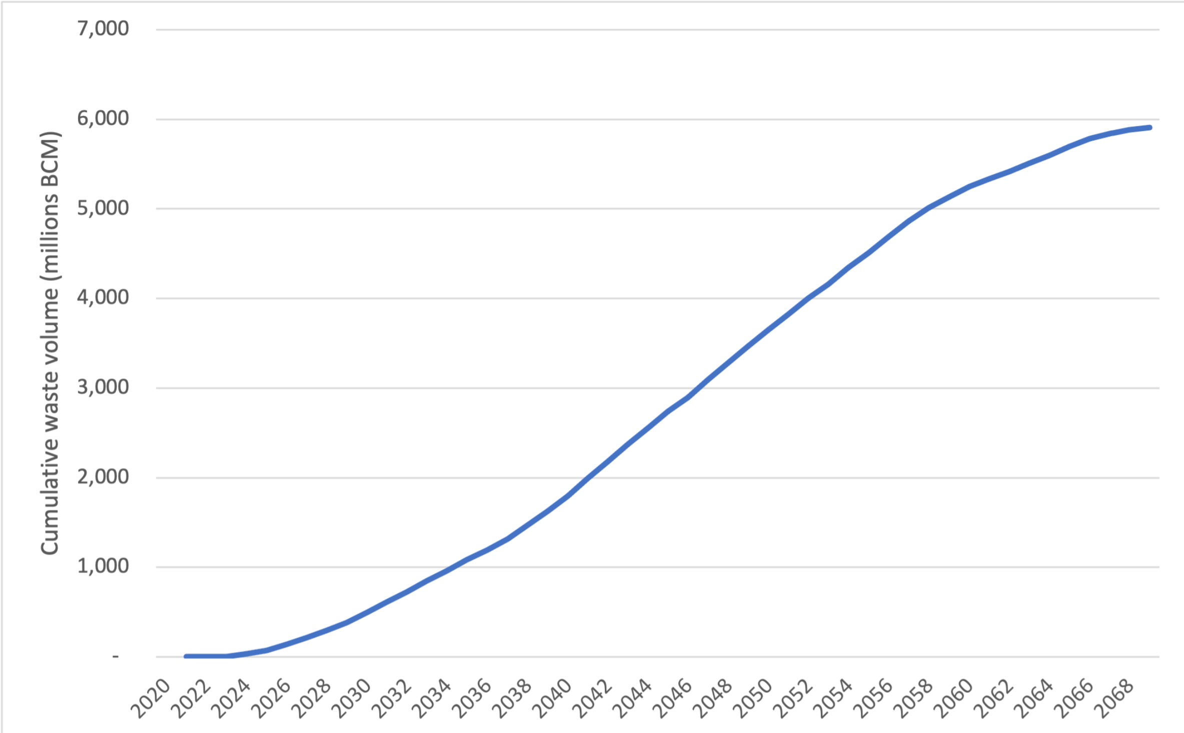


Figure 9.2: Cumulative waste-rock volumes over time in the high-development scenario..

9.1.2 Simulating Se mitigation or attenuation

Mines are proposing a range of technologies to remove Se loads, including deposition of waste rock in saturated, suboxic zones (generally pit backfill), collection and treatment, and alternative waste-rock dump designs. In order to account for these types of mitigation, we simulated reduction rates for Se of 0%, 80%, and 99%. The lack of mitigation modeled as 0% reduction reflects past practice as observed historically in the Elk Valley—this is useful in contextualizing the magnitude of risk should mitigation approaches not perform as expected. A reduction of 80% removal was used as it was also used in sensitivity analyses of Se loads from Grassy Mountain, and 99% was used as it is the base case in the Grassy Mountain Se load model (SRK 2016).

9.1.2.1 Spatial simulation of mine footprints

Spatial extents of the various mining operations were simulated as follows: - Grassy Mountain and Tent Mountain: facility outlines were digitized and imported into the ALCES model based on information provided in the Grassy Mountain Environmental

Impact Assessment and in SRK 2020 (for Tent Mountain). - For other mines, total areas of waste-rock deposition were assumed to be like that of Grassy Mountain, as our scenario assumed similar production rates. Mine extents were simulated to occur within the mine-lease boundaries, and be centred on mapped resource locations or exploration targets provided on company/project websites.

For mines other than Grassy Mountain, the model does not simulate construction of additional footprint associated with processing plants, access roads or rail, or other infrastructure, but focusses on areas of waste-rock deposition.

9.2 References

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